Modelling of RFX-mod shaped tokamak plasmas: from low-β plasmas towards H-mode regime

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Introduction

The RFX-mod device has been recently operated as a Tokamak with circular and shaped plasmas [1]. After preliminary assessment of plasma shape and position controller, the operations were focused to increase the plasma performances towards the H-mode regime. Thus experimental campaigns spanning different plasma regimes, from the naturally low-β to the edge biased induced H-mode plasma [2], were performed. The shape and position control system used in all the experimental campaigns was based on a linearized MIMO plasma response model which was derived from USN low-β equilibrium data through CREATE-L code [3]. These data were not related to real experimental low-β plasmas but only to theoretical low-β equilibrium reproduced by the MAXFEA equilibrium code. The modelling activity is strictly related to the results of the experimental campaigns involving upper single null plasmas because of the presence of an edge polarized electrode on the bottom part of the vacuum chamber. First of all, low-β plasmas have been produced and controlled in vertical position and shape without the presence of the electrode. Then, by inserting the electrode but keeping it turned off, plasmas with increased plasma density have been produced before trying to access the H-mode. These plasmas will be called intermediate-β plasmas and they are characterized by an increased value of poloidal beta, a strong shaping both in horizontal and vertical directions aimed to explore its role in the L-H transition, and a peculiar experimental evidence: the oscillations of the eight distances (gaps) of the plasma boundary from the first wall starting at the time instant of activation of the shape controller and persisting through the whole discharge. This evidence led to disabling the shape control system in the following experimental shots, including the one with the edge biased induced H-mode plasma, and successively to start a modelling activity in order to investigate and develop new plasma response models for plasmas with different dynamics, in first approximation dominated by the increasing values of poloidal beta.

Methodology

Three upper single null experimental plasma shots have been identified as summarized in Tab.1. An iterative procedure for the estimation of the degrees of freedom necessary to produce axisymmetric plasma linearized models by means of the CREATE-L code has been developed and tested. A previous modelling activity of experimental plasmas in the RFX-mod tokamak device, both in circular and shaped configuration, revealed a non-negligible sensitivity of static equilibria on variations of the total plasma current [4]. Therefore, the total plasma current has been set as an additional degree of freedom assuming values up to the experimental uncertainty found on total plasma current, which is the 10% of its experimental measurement (i.e. the value measured by the Rogowski coil). Afterwards, an identification of the key phenomena ruling the evolution of the n=0 vertical instability in the RFX-mod tokamak discharges has been carried out by comparison between the growth rates computed from linearized models with 2D axisymmetric wall (CREATE-L) and linearized models with 3D volumetric wall (CarMa0 [5]). Finally, the axisymmetric plasma linearized models have been analysed in the framework of the control theory revealing peculiar features in terms of associated SISO transfer function for vertical stability control. On the other hand, the full MIMO plasma response model of the intermediate-β plasma (i.e. #39068) was useful to speculate about the experimental oscillations on the eight gaps.

Shot no.	t_{eq} [s]	β_p	n_e [m^{-3}]
36922	0.6	0.1	$6.81 \cdot 10^{17}$
39068	0.4	0.5	$2.35 \cdot 10^{18}$
39123	0.85	1	$4.84 \cdot 10^{18}$

Tab. 1 Experimental plasma shots and equilibrium instants under analysis

Results

The new plasma linearized models revealed a clear sensitivity of the equilibrium on the total plasma current: increased values from 1 to 6% with respect to the measured value were necessary to fit the experimental data in terms of poloidal magnetic fields and plasma boundary reconstruction [6]. The sensitivity level is always lower than the starting level of experimental uncertainty (i.e. 10%) which is obtained by a comparison between the experimental value of the plasma current and the value obtained by performing the discrete line integral of the poloidal magnetic fields measured by the eight pick-up coils at inner surface of the stabilizing shell. The three plasma models exhibit a slow n=0 vertical instability growth rate (<10 s^{-1}) which is consistent with the experimental evidences in RFX-mod [1]. The computed growth rates take into account different number and description of the passive surrounding conducting structures, as summarized in Tab.2.

Shot	γ [s^{-1}]			
number	2D (vessel, shell)	3D (vessel, shell)	2D (vessel, shell, tss)	3D (vessel, shell, tss)
36922	6.17	7.36	5.08	6.48
39068	3.12	3.55	2.56	3.11
39123	5.42	6.18	4.45	5.39

Tab. 2 Computed growth rates for different descriptions of the surrounding passive conductors (vessel, shell and toroidal support structure tss)

It can be noticed that by introducing the toroidal support structure in the models, the growth rate is slowed down by a factor up to 18% with respect to the case with only the vessel and shell as passive conductors. Comparisons between 2D and 3D results of Tab.2 show that the shell gaps on the inner equatorial plane have a destabilizing effect with an increasing of the mode growth rate up to 16% with respect to the 2D case. Beyond the decreasing values of growth rate for plasmas with increased values of β_p, it is interesting to note that the structure of the unstable mode, represented by a pattern of current on the passive conductors, is significantly different for the three shots as shown in Fig.1. In particular, the low-β plasma (i.e. #36922) has a typical antisymmetric pattern of currents on the passive conductors upper and lower with respect to the equatorial plane, representing a VDE [7]. Instead, the intermediate-β plasma (i.e. #39068) is characterized by a pattern spanning the conductors in all the poloidal angles, involving in particular the conductors on the outer and inner side of the equatorial plane. This feature is more evident in the H-mode plasma (i.e. #39123) where the VDE antisymmetric components are smaller while the one related to the outer and inner side are stronger. The outer-inner pattern is typically associated to horizontal displacement events. A superposition of it with a VDE may be possible in these plasmas with increased β_p since they present a strong shaping also along the equatorial

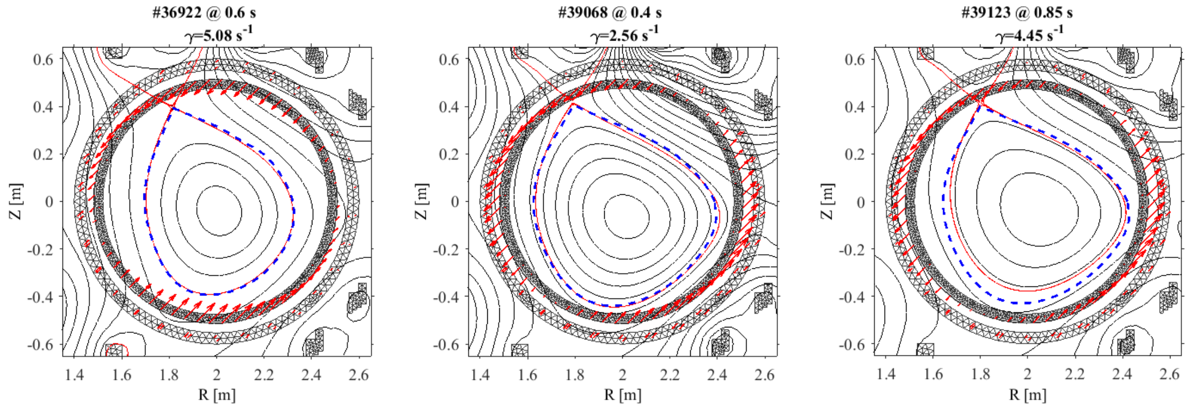

Fig. 1 Plasma equilibrium computed boundary (red) and reconstructed (blue) with current pattern on passive conductors (red arrows) associated to unstable mode structure for each experimental shot

plane, as shown in Fig.1. It seems that a more uniform distribution of the mode along the poloidal angle, as shown in Fig.1, leads to a slower growth rate of the instability. Finally, for control system purposes, a SISO model of the three plasma is obtained from the state space MIMO model by selecting the proper input/output related to the control of the vertical position. It is interesting to note that the SISO models of the intermediate-β and H-mode plasma revealed to be non-minimum phase systems, which means that their transfer functions have zeros in the right-hand s-plane instead the low-β plasma models have not. This puts a serious limitation on robust stability of the feedback system since a simple proportional gain is not able to stabilize the unstable mode of shot #39068 and #39123. Fig.2 shows that by increasing the value of the gain, the mode slows down but not enough to be stabilized because it saturates at the value of the positive zero. In this picture, the zero works as a center of attraction for the unstable pole, preserving its position on the right half of the s-plane or equivalently its unstable condition. It is important to stress that these slow growth rates have not be seen in the experimental discharge reasonably because the instability behaves on a time scale much longer than the time interval of the plasma discharge. Therefore, assuming the plasma vertically stable, the intermediate-β plasma model has been used to investigate the plasma gap oscillations, which may be hypothesized as a reflection of the pulsed gas puffing control. In fact, the gas puffing has a time scale comparable with the oscillations one. Further analysis on these new plasma linearized model will be useful to confirm this picture and to redefine the overall tokamak control system of RFX-mod device for future experimental sessions.

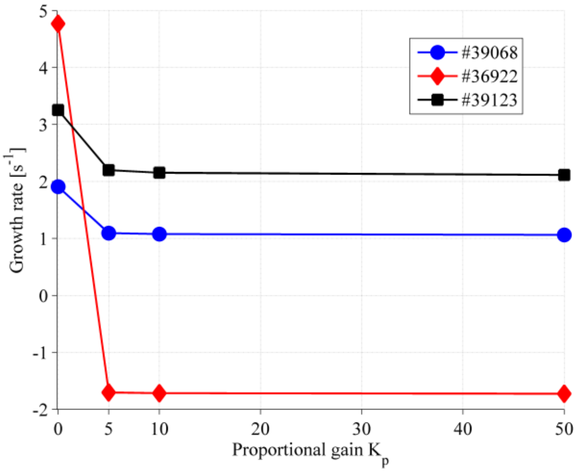

Fig. 2 Asymptotic independence of the growth rates from the gain

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